



Multinomial Processing Tree (MPT) Modeling, Part 3: Advanced Features of multiTree

Edgar Erdfelder and Daniel W. Heck

University of Mannheim & Phillips University Marburg

3) Advanced features of multiTree

- 3.1) Identifiability checks in multiTree
- 3.2) Statistical power analyses
- 3.3) Model selection

3.1) Identifiability checks in multiTree

- Get Jacobian
 - Evaluate at random parameter location
 - Use parameter values from parameter tab
- Repeated analysis
 - Check stability of parameters estimates for a specific vector of observed frequencies
- Simulated identifiability
 - Repeated data generation for different random locations in Ω , followed by estimation

3.2) Statistical power analyses

Traditional Power Analysis (Cohen, 1969, 1972, 1988)

- Under H_1 , any Power-Divergence statistic (S_λ) follows a noncentral chi-square distribution with noncentrality parameter $\gamma_{(\lambda)} = N \cdot \mathbf{w}_{(\lambda)}^2$, where $\mathbf{w}_{(\lambda)}$ denotes the effect size $\mathbf{w}_{(\lambda)}^2 = S_\lambda(\Theta) / N$
- Effect size conventions
 - $w = .10$ (“small effect“)
 - $w = .30$ (“medium effect“)
 - $w = .50$ (“large effect“)
- Types of power analysis
 - “A priori”: Compute N as a function of w , α , and $1-\beta$
 - “Post hoc”: Compute $1-\beta$ as a function of w , α , and N

Problems of the traditional method

- Problem 1:
 - How does effect size translate into (differences between) parameter values?
- Problem 2:
 - Do effect size labels have the same meaning in different models?
- Problem 3:
 - The relative size of groups (conditions) is ignored.

Cohen (1988, p. 244)

On w effect sizes conventions:

“Their use requires particular caution, since, apart from their possible inaptness in a particular substantive context, what is subjectively the same degree of departure or degree of correlation (...) may yield varying w , and conversely. **The investigator is best advised to use the conventional definitions as a general frame of reference (...) and not to take them too literally.**”

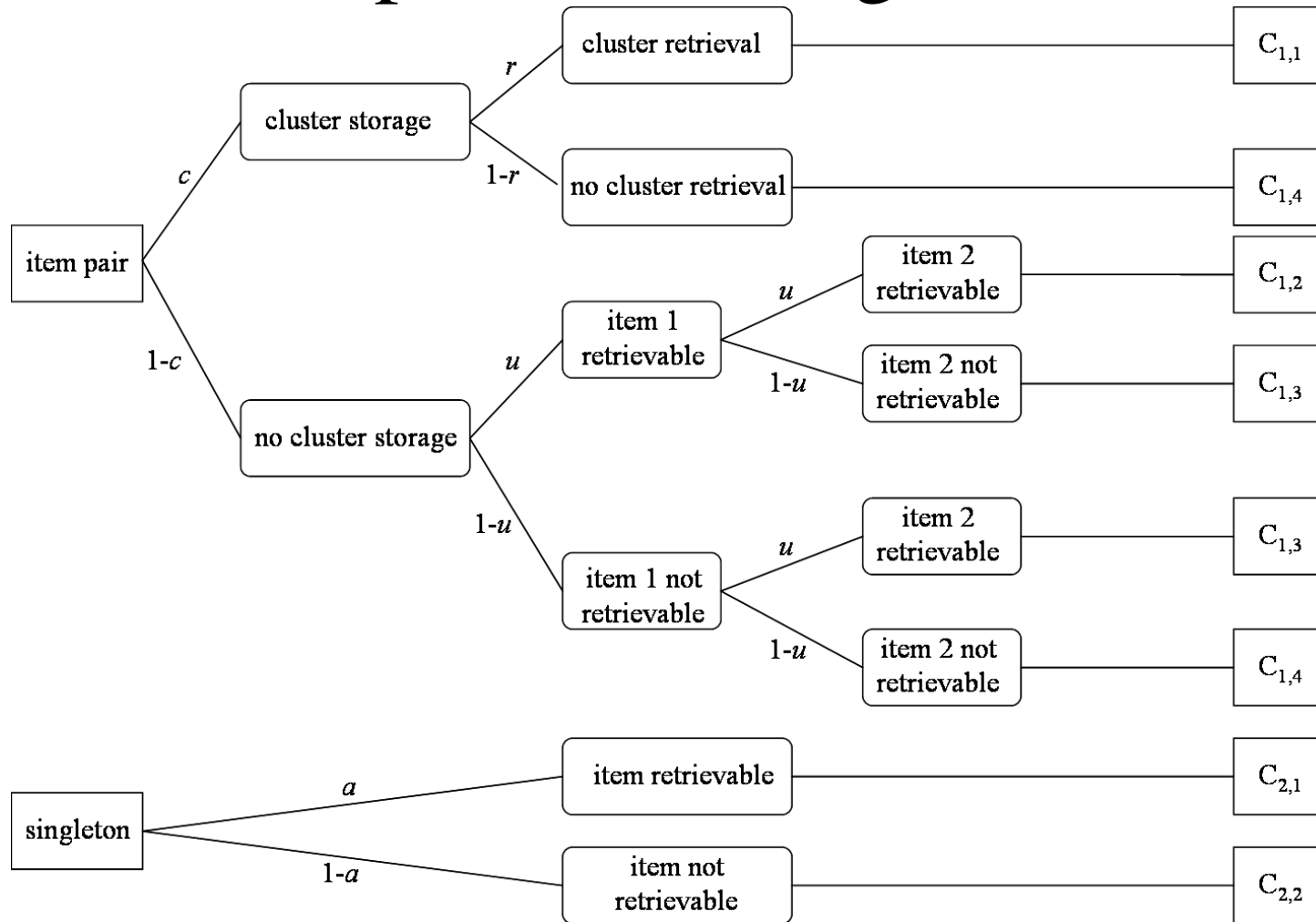
Approach 2: Power as a function of the model parameters under H_1

- 1) Specify your H_0 model
- 2) Specify your H_1 model with all parameter values fixed at „plausible values“
- 3) Choose $N_k, k = 1, \dots, K$, and calculate expected frequencies under H_1
- 4) Fit the H_0 model to the H_1 expected frequencies by minimizing PD^λ for your choice of λ
- 5) Use the minimum PD^λ value as the noncentrality parameter $\gamma_{(\lambda)}$
- 6) Compute $1-\beta(\pi) = Pr(\chi^2(\gamma_{(\lambda)}, df) \geq c_{(df, \alpha)})$

Open questions

- How well does Approach 2 work for joint MPT models?
- How does approximation quality depend on the sample sizes?
- Does the approximation quality depend on the PD^λ test statistic used?

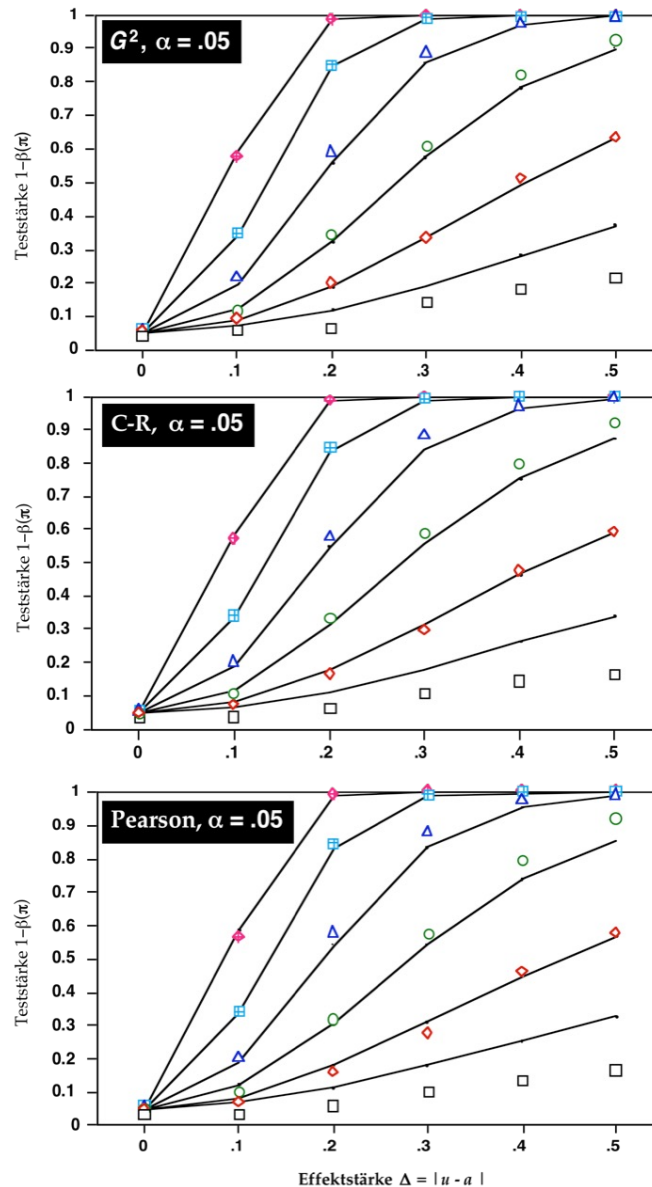
Let's return to our running example: The pair clustering model



A Monte-Carlo study

- Storage-retrieval model ($\tau_1 = 2/3$, $\tau_2 = 1/3$)
- $H_0: u = a$, $df = 4 - 3 = 1$
- $H_1: c = r = .5$, $u = .5 - \Delta/2$, $a = .5 + \Delta/2$, for
 $\Delta = .00 / .10 / .20 / .30 / .40 / .50$
($w = .00 / .07 / .13 / .19 / .24 / .28$)
- $N = 30 / 60 / 120 / 240 / 480 / 960$
- Type-1 errors $\alpha = .01 / .05$
- Statistics: G^2 , X^2 , Cressie-Read
- 1000 Monte Carlo samples per run

Results for $\alpha = .05$



- *Symbols:* Monte-Carlo estimated power for G^2 (top), Cressie-Read (middle), and X^2 (bottom).
- *Black lines:* Approximate power using same λ in $\text{ncp } \gamma_{(\lambda)}$ as in PD^λ test statistic
- Sample sizes from top to bottom:
 - $N = 960$
 - $N = 480$
 - $N = 240$
 - $N = 120$
 - $N = 60$
 - $N = 30$

Absolute differences between Monte-Carlo power and approximate power formula ($\alpha = .05$)

	Test statistic used					
	G^2		$C-R$		X^2	
N	mean	max.	mean	max.	mean	max.
30	.065	.157	.075	.173	.078	.162
60	.007	.019	.010	.020	.015	.032
120	.021	.040	.027	.049	.031	.066
240	.017	.031	.020	.041	.021	.048
480	.004	.011	.005	.010	.006	.014
960	.003	.014	.003	.014	.004	.016
Mean	.020	.045	.023	.051	.026	.056

Conclusions from the Monte-Carlo study

- In our example, the power approximation is acceptable for $N > 50$ and good for $N > 200$
- Approximation accuracy appears to be worse for $\alpha = .01$ compared to $\alpha = .05$
- Approximation accuracy is slightly larger for G^2 compared to both the Cressie-Read statistic and Pearson's X^2 .
- Hence, G^2 can safely be used as a goodness-of-fit statistics combined with $\alpha = .05$ and power analyses based on the parameter values under H_1 (as sketched above).
- Prior to each study, the N per tree of the MPT model should be determined that yields sufficient power for key χ^2 tests applied to model parameters.

Power optimization

Problem:

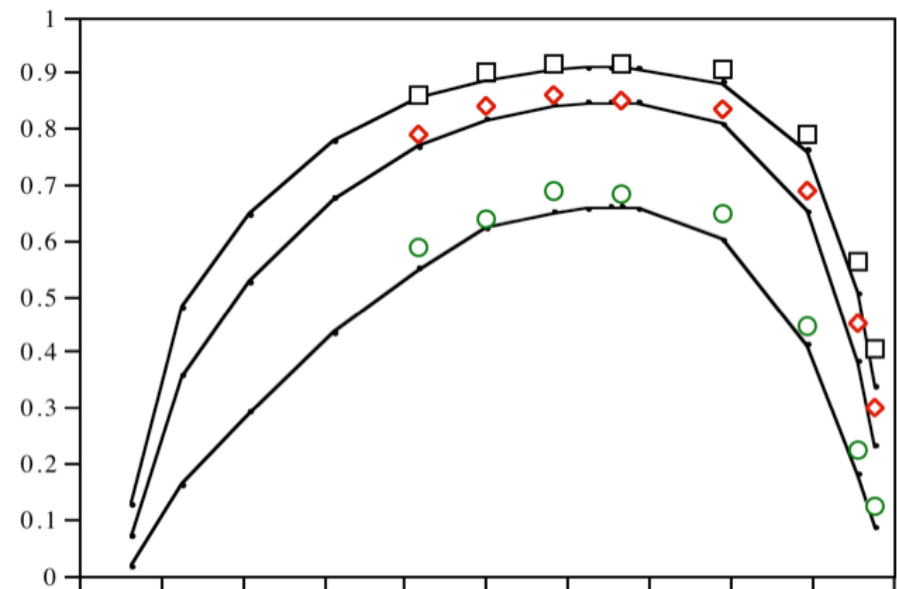
Given a fixed total sample size and a fixed α , is there any way to maximize the power?

Answer:

Yes, there is!

1) τ_k Optimization

- Power of G^2 as a function of τ_1 for the storage retrieval model, given $\alpha = .10$ (top), $.05$ (middle) and $.01$ (bottom).
- $c = r = .50, u = .40, a = .60$
- $N = 480$
- Conclusions:
 - Strong effect of τ_1 !!
 - Max. power for $\tau_1 = .652$
 - Thus, $\tau_1 = \dots = \tau_K$ may be a bad default option!



2) θ Optimization

- Model parameters can be divided in H_0 -relevant and H_0 -irrelevant parameters. For the pair-clustering model test:
 - u and a are H_0 relevant
 - c and r are H_0 irrelevant
- Problem:

How to choose the values of the H_0 -irrelevant parameters so as to maximize the power of the model test?

Approximate power of the G^2 test for the storage-retrieval model ($\alpha = .05$, $N_1 = 320$, $N_2 = 160$)

Parameter values under H_1				ncp	approx
c	r	u	a	$\gamma_{(0)}$	$1-\beta(\pi)$
.10	.80	.40	.60	12.49	.94
.10	.20	.40	.60	12.49	.94
.50	.80	.40	.60	8.92	.85
.50	.20	.40	.60	8.92	.85
.90	.80	.40	.60	2.53	.36
.90	.20	.40	.60	2.53	.36

3) Power of conditional versus unconditional tests

- Consider two nested models:

- M_0 with parameter space Ω_0
- M_1 with parameter space Ω_1
- $\Omega_1 \subset \Omega_0$

- Problem:

M_1 can be tested by an unconditional or a conditional G^2 test provided that M_0 holds.
Which test is more powerful?

Running example: pair-clustering model

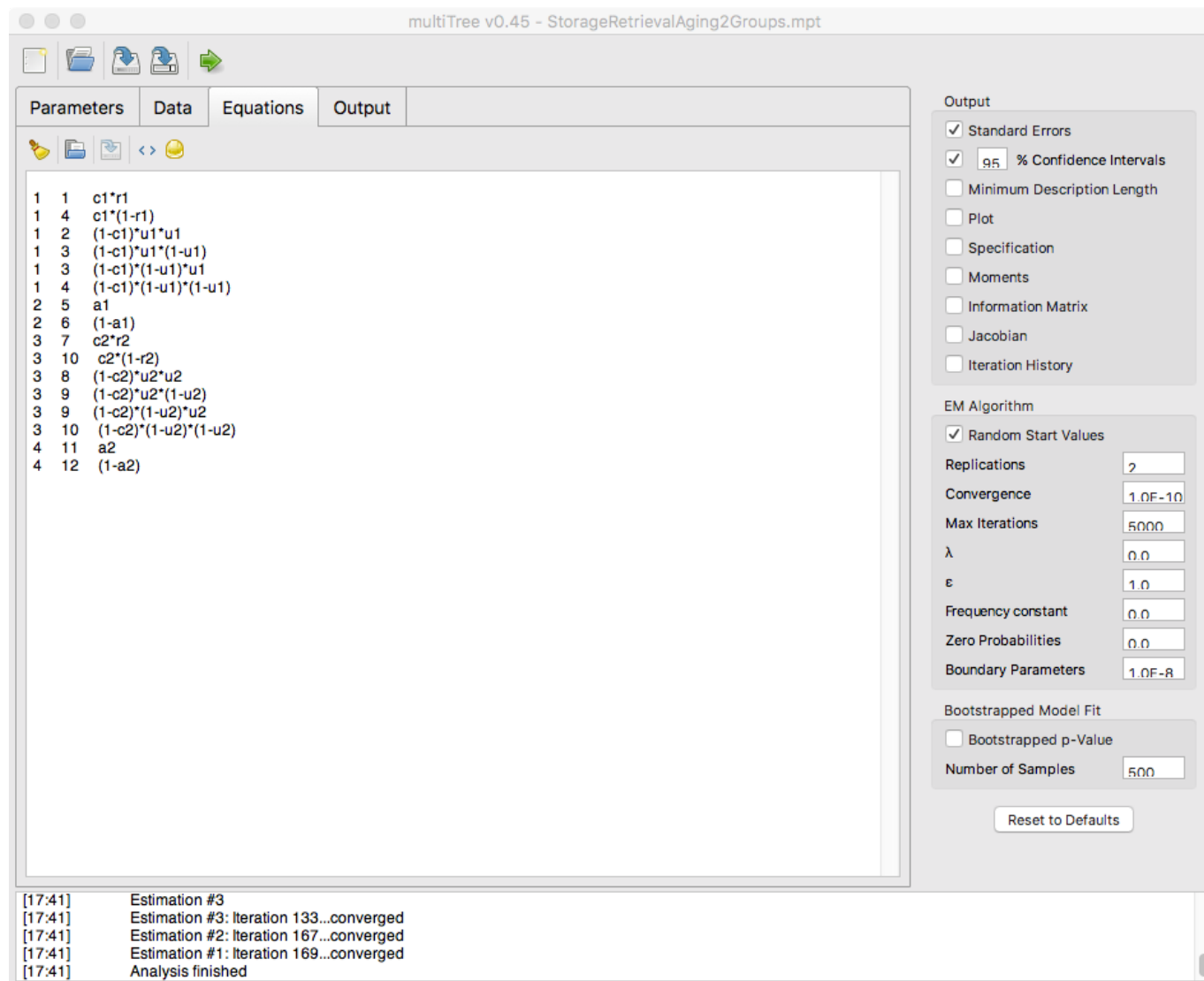
- $N_1 = 160, N_2 = 80$
- $M_0: u = a$
- $M_1: u = a$ and $c = .30$
- Under $H_1: c = r = u = a = .50$ we obtain ($\alpha = .05$):
 - $G^2(M_1)$: $df = 4-2 = 2, \gamma_{(0)} = 8.62, 1-\beta(\pi) = .75$
 - $G^2(M_1)-G^2(M_0)$: $df = 2-1 = 1, \gamma_{(0)} = 8.62, 1-\beta(\pi) = .85$
- Therefore, use conditional G^2 difference tests whenever possible as they are more powerful.

Summary and conclusions

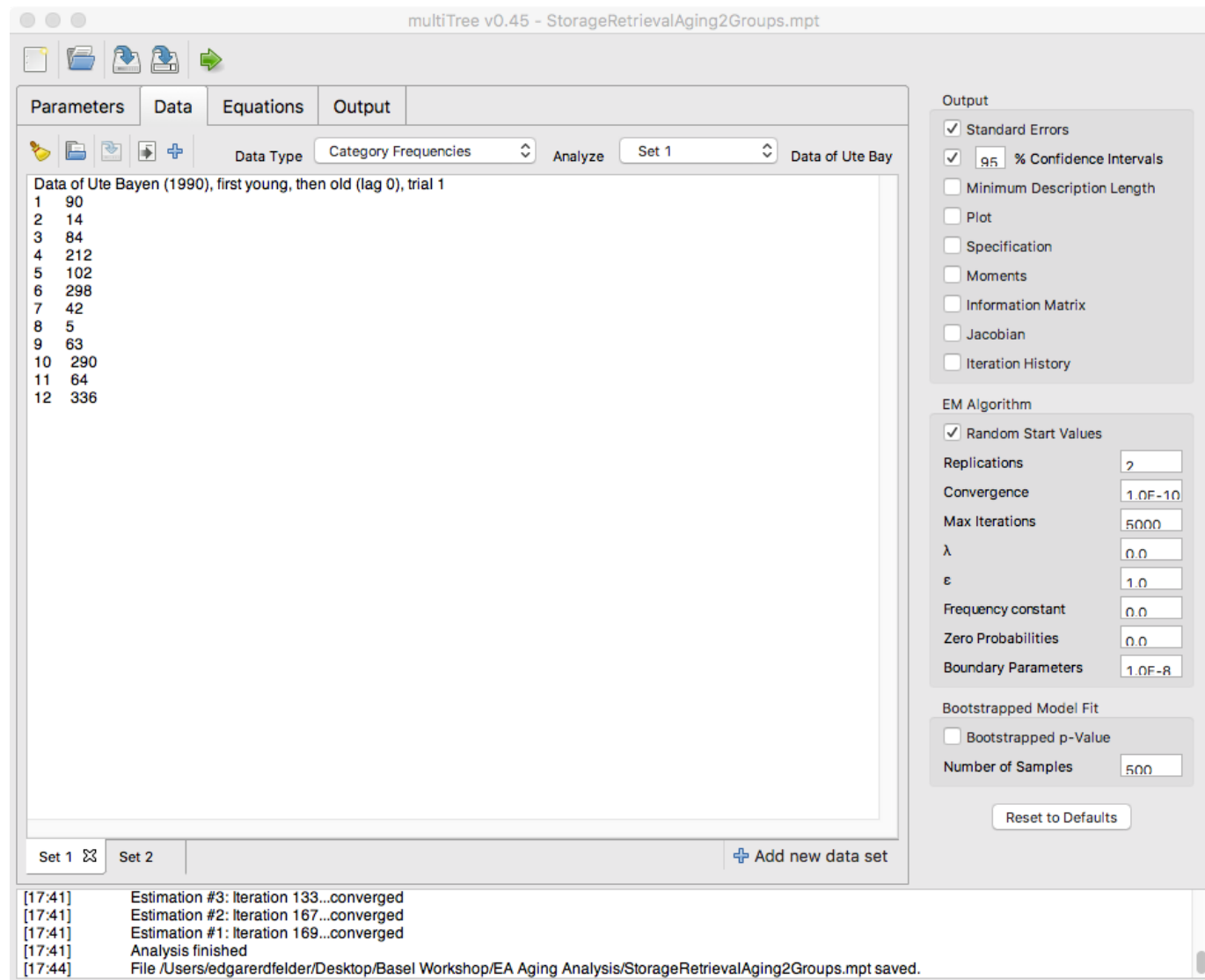
- Do not ignore the power of model tests!
- The proposed approximation method works very well for joint MPT models with typical sample sizes
- G^2 is a good default option for several reasons:
 - Approximation accuracy is optimal
 - Maximum power for “diffuse” noncentrality structures
 - Option of conditional tests
- Do not forget to optimize context conditions:
 - τ_k optimization
 - θ optimization
 - conditional tests whenever possible.

A priori and post-hoc power
analyses using multiTree

Example: Age group comparison



Example: Age group comparison



Definition of baseline model

multiTree v0.45 - StorageRetrievalAging2Groups.mpt

Parameters Data Equations Output

Hierarchical Model Families

☒ Define current model as new baseline model (needs to be estimated before it can serve as a baseline).

☐ Compare current model against baseline model

a1	= u1	0.25431
a2	= u2	0.15795
c1	free	0.44815
c2	free	0.41565
r1	free	0.50205
r2	free	0.25265
u1	free	0.25431
u2	free	0.15795

Specification

Number of trees	4
Number of categories	12
Number of free categories	8
Number of parameters	8
Number of constrained parameters	2
Degrees of freedom	2

Output

☒ Standard Errors

☒ 95 % Confidence Intervals

☐ Minimum Description Length

☐ Plot

☐ Specification

☐ Moments

☐ Information Matrix

☐ Jacobian

☐ Iteration History

EM Algorithm

☒ Random Start Values

Replications 2

Convergence 1.0E-10

Max Iterations 5000

λ 0.0

ϵ 1.0

Frequency constant 0.0

Zero Probabilities 0.0

Boundary Parameters 1.0E-8

Bootstrapped Model Fit

☐ Bootstrapped p-Value

Number of Samples 500

Reset to Defaults

[17:48] Estimation #2
[17:48] Estimation #1: Iteration 158...converged
[17:48] Estimation #3: Iteration 164...converged
[17:48] Estimation #2: Iteration 197...converged
[17:48] Analysis finished

H_0 : No age differences in retrieval

multiTree v0.45 - StorageRetrievalAging2Groups.mpt

Parameters Data Equations Output

Hierarchical Model Families

☐ Define current model as new baseline model (needs to be estimated before it can serve as a baseline).

☒ Compare current model against baseline model

a1	= u1	0.26008
a2	= u2	0.13548
c1	free	0.47148
c2	free	0.23597
r1	free	0.46647
r2	= r1	0.46647
u1	free	0.26008
u2	free	0.13548

Specification

Number of trees	4
Number of categories	12
Number of free categories	8
Number of parameters	8
Number of constrained parameters	3
Degrees of freedom	3

Output

☒ Standard Errors

☒ 95 % Confidence Intervals

☐ Minimum Description Length

☐ Plot

☐ Specification

☐ Moments

☐ Information Matrix

☐ Jacobian

☐ Iteration History

EM Algorithm

☒ Random Start Values

Replications 2

Convergence 1.0E-10

Max Iterations 5000

λ 0.0

ϵ 1.0

Frequency constant 0.0

Zero Probabilities 0.0

Boundary Parameters 1.0E-8

Bootstrapped Model Fit

☐ Bootstrapped p-Value

Number of Samples 500

Reset to Defaults

[17:37] Estimation #3
[17:37] Estimation #2: Iteration 116...converged
[17:37] Estimation #1: Iteration 139...converged
[17:37] Estimation #3: Iteration 140...converged
[17:37] Analysis finished

Is insignificant outcome due to lack of power?

The screenshot displays the multiTree v0.45 software interface. The main window is titled "multiTree v0.45 - StorageRetrievalAging2Groups.mpt". It features a tabbed interface with "Parameters", "Data", "Equations", and "Output" tabs. The "Output" tab is active, showing the following results:

Model Fit

PD^{lambda}=0.0 (df=3) = 3.92165 p = 0.27005

ln(likelihood) = -1178.07830
AIC = 2366.15661
BIC = 2393.04540
Delta AIC = -2.07835
Delta BIC = -18.21163

Difference to Baseline Model

PD^{lambda}=0.0 (df=1) = 3.76626 p = 0.05230

AIC difference = 1.76626
BIC difference = -3.61150
Ratio of AIC weights = 0.29253
Ratio of BIC weights = 0.85885

Parameters

	Baseline	Current
a1	= u1	= u1
a2	= u2	= u2
c1	free	free
c2	free	free

Output Options

- ☒ Standard Errors
- ☒ 95 % Confidence Intervals
- ☐ Minimum Description Length
- ☐ Plot
- ☐ Specification
- ☐ Moments
- ☐ Information Matrix
- ☐ Jacobian
- ☐ Iteration History

EM Algorithm

- ☒ Random Start Values
- Replications: 2
- Convergence: 1.0E-10
- Max Iterations: 5000
- λ : 0.0
- ϵ : 1.0
- Frequency constant: 0.0
- Zero Probabilities: 0.0
- Boundary Parameters: 1.0E-8

Bootstrapped Model Fit

- ☐ Bootstrapped p-Value
- Number of Samples: 500

Log Output

```
[17:37] Estimation #3  
[17:37] Estimation #2: Iteration 116...converged  
[17:37] Estimation #1: Iteration 139...converged  
[17:37] Estimation #3: Iteration 140...converged  
[17:37] Analysis finished
```

multiTree power analysis window

Power Analysis

Statistical power of a test is defined as the probability of rejecting a null hypothesis if it is in fact false, and depends on the alpha error, effect size, and sample size. To perform a power analysis, 'true' population values of the parameters, a H1 model and a H0 model need to be specified. The H1 model is usually chosen such that it yields a perfect fit to the data. The H0 model represents a more restrictive hierarchically nested model. The additional constraints inherent in the H0 model compared to those of the H1 model finally define the particular null hypothesis of interest. That is, the calculated power expresses the probability to reject this additional constraint if it is in fact false.

Type of power analysis

☒ A-priori: Compute required sample size given power, alpha, and effect size.

☐ Post-hoc: Compute achieved power given sample size, alpha, and effect size.

Alpha error probability: 0.05

Desired power (ignored in post-hoc power analysis): 0.95

Please specify the parameter values in the population as well as the H1 and the H0 model:

c1	0.44813	free	0.44813	free	0.44813
c2	0.41563	free	0.41563	free	0.41563
r1	0.50209	free	0.50209	free	0.50209
r2	0.25263	free	0.25263	= r1	0.25263

Please enter the number of observations (represent weights in a-priori power analysis)

Tree: 1 400.0

Tree: 2 400.0

Tree: 3 400.0

OK Cancel

multiTree power analysis output

multiTree v0.45 - StorageRetrievalAging2GroupsPowerBeispiel.mpt

Parameters Data Equations Output

Population H1 H0

a1	= 0.25431	= u1	= u1
a2	= 0.15793	= u2	= u2
c1	= 0.44813	free	free
c2	= 0.41563	free	free
r1	= 0.50209	free	free
r2	= 0.25263	free	= r1
u1	= 0.25431	free	free
u2	= 0.15793	free	free

Required number of observations = 5613.62096
Required observations per tree:

Tree: 1 = 1403.40524
Tree: 2 = 1403.40524
Tree: 3 = 1403.40524
Tree: 4 = 1403.40524

Model Fit

H0 Model $PD^{\lambda=0.0}$ (df=3) = 13.21474
H1 Model $PD^{\lambda=0.0}$ (df=2) = 0.00000

Effect size w = 0.04852
Non-centrality parameter = 13.21474
Critical Chi-square = 3.84146
Delta df = 1

Output

☒ Standard Errors
☒ 95 % Confidence Intervals
☐ Minimum Description Length
☐ Plot
☐ Specification
☐ Moments
☐ Information Matrix
☐ Jacobian
☐ Iteration History

EM Algorithm

☒ Random Start Values

Replications 2
Convergence 1.0E-10
Max Iterations 5000
 λ 0.0
 ϵ 1.0
Frequency constant 0.0
Zero Probabilities 0.0
Boundary Parameters 1.0E-8

Bootstrapped Model Fit

☐ Bootstrapped p-Value
Number of Samples 500

Reset to Defaults

[14:28] Running power analysis... target ncp = 12.9947 current ncp = 1.73102
[14:28] Running power analysis... target ncp = 12.9947 current ncp = 3.68079
[14:28] Running power analysis... target ncp = 12.9947 current ncp = 7.10904
[14:28] Running power analysis... target ncp = 12.9947 current ncp = 11.29318
[14:28] Power analysis finished.

3.3) Model selection

- Basic idea: Select the model that fits best *after correcting for model complexity/flexibility*
- Three Options:
- Penalty for S : Akaike Information Criterion (AIC)
 - $\text{AIC}(M_0) = -2 \cdot \ln(L(\theta; y)) + 2 \cdot S$
- Penalty for S taking N into account: Bayesian Information Criterion (BIC):
 - $\text{BIC}(M_0) = -2 \cdot \ln(L(\theta; y)) + S \cdot \ln(N)$
- Penalty for S taking N and complexity due to functional form into account: Normalized Maximum Likelihood (NML)

Normalized Maximum Likelihood (NML)

An implementation of the MDL principle was provided by [Rissanen \(2001\)](#) who derived the normalized maximum likelihood (NML) to measure the stochastic complexity of a model given a data set,

$$\text{NML} = -\text{LML} + C_{\text{NML}}(N), \quad (1)$$

where the maximum log-likelihood (LML) as a measure of fit is weighted against the complexity term

$$C_{\text{NML}}(N) = \ln \int_{\mathcal{X}^N} f(\mathbf{x}|\hat{\boldsymbol{\theta}}(\mathbf{x})) d\mathbf{x}. \quad (2)$$

This complexity term is the natural logarithm of the integral over the maximum likelihoods across the whole outcome space \mathcal{X}^N of potentially observable vectors \mathbf{x} with N observations. Accordingly, a complex model that fits a wide range of observable data vectors will have a large value of $C_{\text{NML}}(N)$ compared to a model that fits only a small subset of observable data ([Myung, Navarro, & Pitt, 2006](#)). Unfortunately, there is no general closed-form expression of $C_{\text{NML}}(N)$ and numerical estimation techniques such as Monte Carlo (MC) integration are often too time intensive for practical purposes. An alternative is the Fisher information approximation (FIA; [Rissanen, 1996](#)),

$$\text{FIA} = -\text{LML} + C_{\text{FIA}}(N), \quad (3)$$

which is asymptotically equivalent to NML. The complexity term $C_{\text{FIA}}(N)$ covers the number of free parameters S and the number of observations N in the first summand and considers the functional form of the model in the second,

$$C_{\text{FIA}}(N) = \frac{S}{2} \ln \left(\frac{N}{2\pi} \right) + \ln \int_{\Omega} \sqrt{|\mathbf{I}(\boldsymbol{\theta})|} d\boldsymbol{\theta}, \quad (4)$$

where $\mathbf{I}(\boldsymbol{\theta})$ is the Fisher information matrix of sample size one. This

Heck, Moshagen & Erdfelder (2014)

To avoid biases in model selection using FIA for NML stable models, we propose to check whether the $C_{\text{FIA}}(N)$ rank order of the candidate models is invariant across different numbers N of observations. Based on the definition of FIA in (4) it is easy to show that for any two models with a fixed but unequal number of parameters S_i and S_j , respectively, the $C_{\text{FIA}}(N)$ rank order cannot be identical for all possible sample sizes. Since the integral in (4) is independent of N , it is straightforward to determine the (single) sample size $N'_{i,j}$ for which the complexity terms of two models with $S_i \neq S_j$ are equal. Equating the FIA terms of two models i and j and solving for N yields

$$N'_{i,j} = 2\pi \exp \left[\frac{2}{S_i - S_j} \left(\ln \int_{\Omega_j} \sqrt{|\mathbf{I}_j(\boldsymbol{\theta})|} d\boldsymbol{\theta} - \ln \int_{\Omega_i} \sqrt{|\mathbf{I}_i(\boldsymbol{\theta})|} d\boldsymbol{\theta} \right) \right]. \quad (5)$$

When $N > N'_{i,j}$, the $C_{\text{FIA}}(N)$ terms of the two competing models i and j will always result in the same rank order. Because $C_{\text{FIA}}(N)$ approximates $C_{\text{NML}}(N)$ for increasing N , this must be the correct (i.e., NML-consistent) rank order. By implication, for any $N < N'_{i,j}$ the rank order of complexity terms is incorrectly inverted.

Heck, Moshagen & Erdfelder (2014)

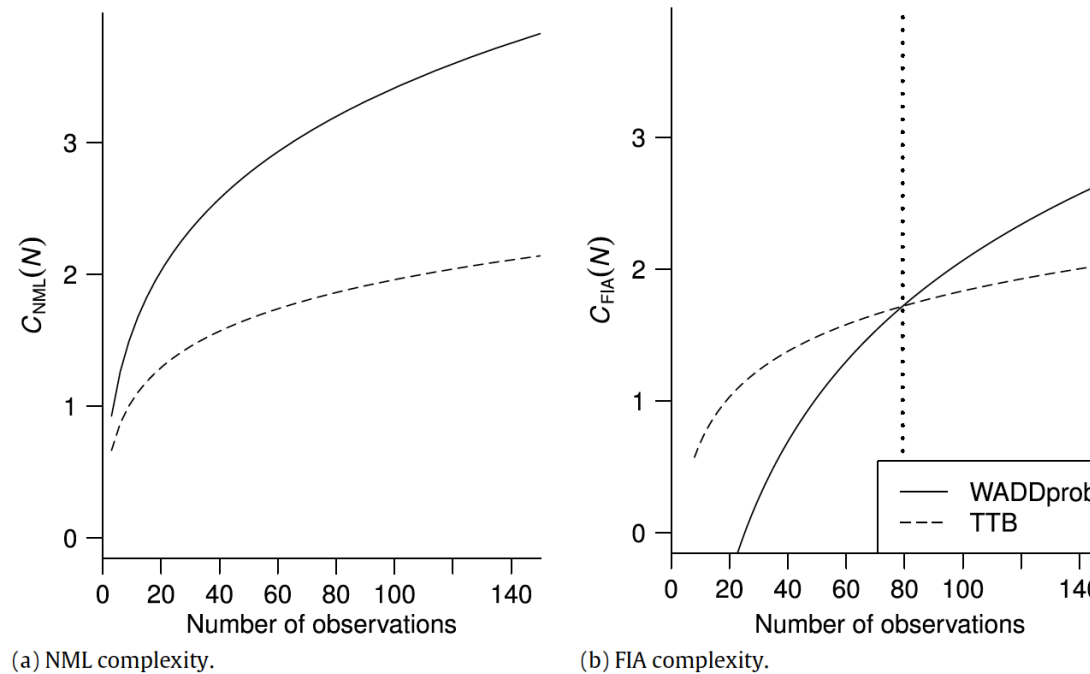


Fig. 1. NML and FIA complexities for two decision strategies, take-the-best (TTB) and a probabilistic weighted-additive rule (WADDprob; Fig. 4), as functions of the number of observations N . The dotted vertical line for FIA marks the lower bound $N' = 80$.